# Coupled Euler-Lagrange Modeling of Buried Structure Response to Blast Loading

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# Overview

- Model response of a buried reinforced concrete structure to close-in detonation of a conventional explosive charge

- Many approaches exist for modeling blast/structure interaction
  - Engineering models, FE, Euler, ALE, CEL, FE/SPH, etc.
  - One-way coupling often used
    - Works well when the load duration is short compared to the response time of the structure
    - Problematic for long duration loading or complex structure geometries
  - Fully coupled analyses becoming more common

- Current work uses the coupled Euler-Lagrange (CEL) solution approach embedded within the Zapotec code
  - Investigate utility of CEL algorithm via benchmark calculations
  - Benchmarks derived from CONWEB test series

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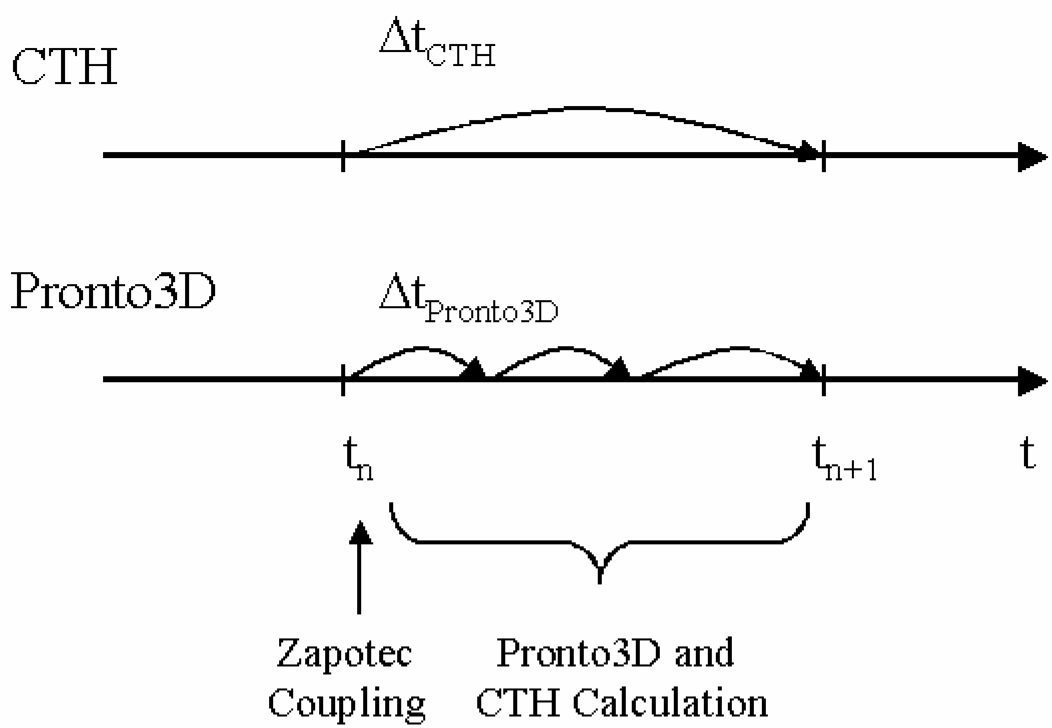
# What is Zapotec?

- Coupled Euler-Lagrange computer code
- Directly couples two production codes
  - CTH: Eulerian shock physics code
  - Pronto3D: Explicit, Lagrangian FE code
- Zapotec couples interaction between Lagrangian and Eulerian materials

# Zapotec Background
# The Coupled Algorithm in Time

- CTH and Pronto3D are run sequentially, cycle by cycle
- Algorithm permits Pronto3D subcycling



# The Zapotec Coupling Algorithm

- Coupled treatment conducted in two steps, referred to as material insertion and force application

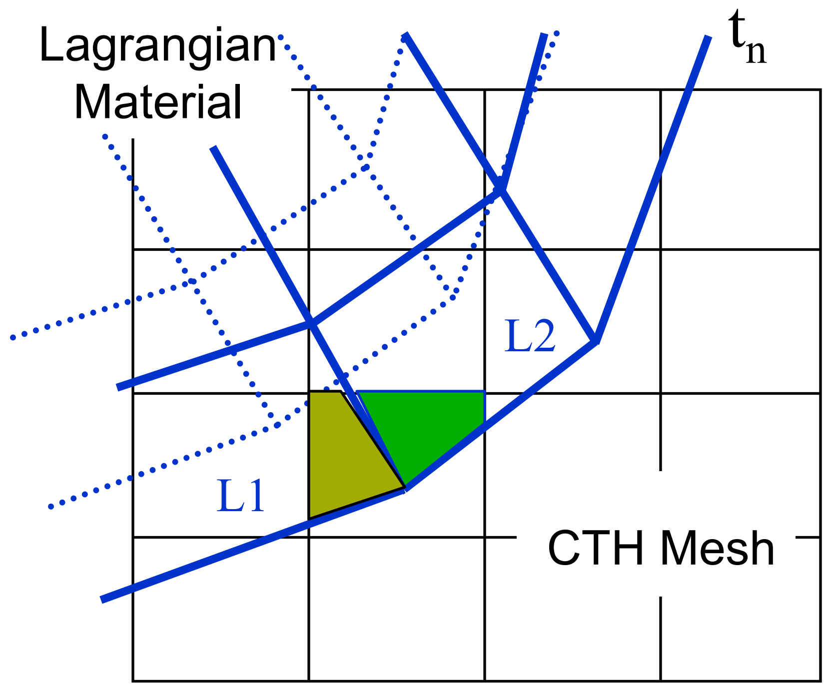
- Material insertion step updates CTH data

- Force application step updates Pronto3D data

## The Zapotec Coupling Algorithm

# Material Insertion Step

- Remove pre-existing Lagrangian material from the CTH mesh
- **Get updated Lagrangian data**
- **Insert Lagrangian material into CTH mesh**
  - Compute volume overlaps
  - Map Lagrangian data – mass, momentum, sound speed, stress, internal energy

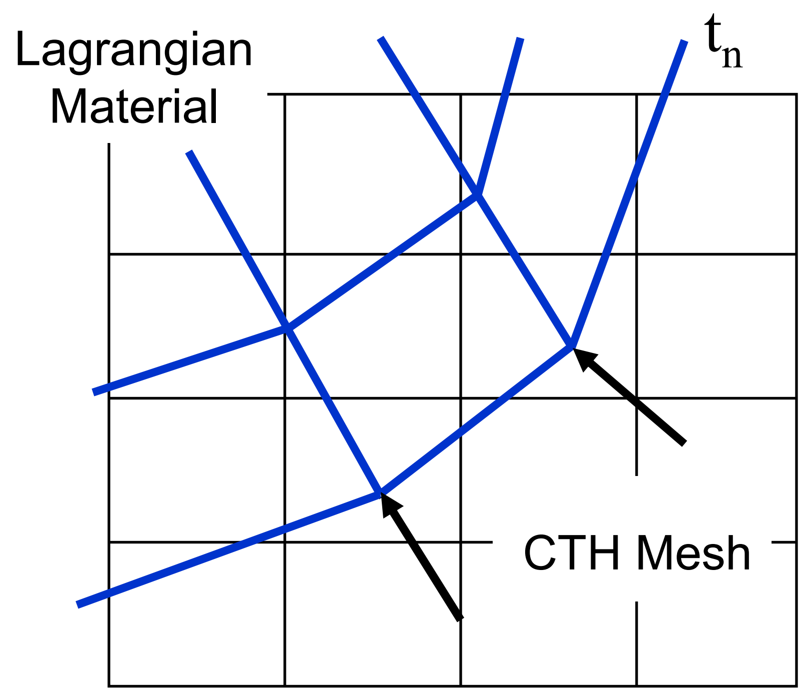



$$P_{L,inserted} = (V_{O,L1}\, P_{L1} + V_{O,L2}\, P_{L2}) / V_O$$

$$V_{overlap} = V_O = V_{O,L1} + V_{O,L2}$$

## The Zapotec Coupling Algorithm
# Force Application Step

- Remove pre-existing Lagrangian material from the CTH mesh
- Get updated Lagrangian data
- Insert Lagrangian material into CTH mesh
  - Compute volume overlaps
  - Map Lagrangian data
- **Compute external force on Lagrangian surface**
  - Determine surface overlaps
  - Compute surface tractions based on Eulerian stress state
  - Compute normal force on element surface (element-centered force)
  - If friction, compute tangential force as $\mathbf{f}_t = \mu f_n \mathbf{s}$
  - Distribute forces to nodes




$$\mathbf{f}_n = (\mathbf{t} \cdot \mathbf{n}_L)\, A_{overlap}\, \mathbf{n}_L$$

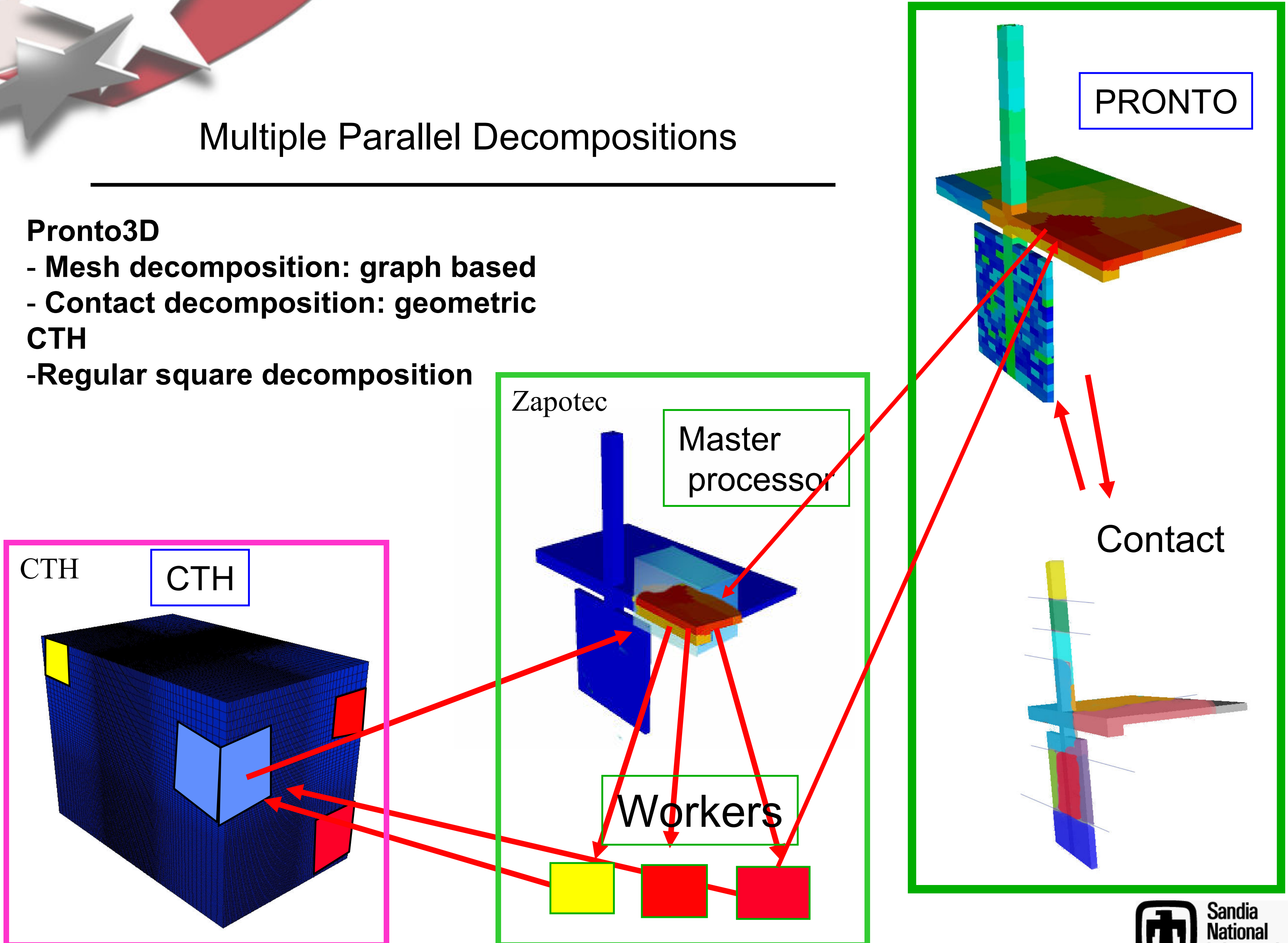
$$\mathbf{f}_I = N_I\, \mathbf{f}_n$$

# Highlight of Capabilities

- Supports several Pronto3D element types
  - 8-node hexahedral element
  - 8-node tetrahedral element
  - 4-node shell element
- Zapotec coupling with AMR-CTH
  - Allows adaptivity on structured mesh
- Parallel implementation
  - Pronto3D and CTH use different mesh decompositions
  - Coordinate data transfer between Pronto3D and CTH
  - Dynamic load balance of transferred data

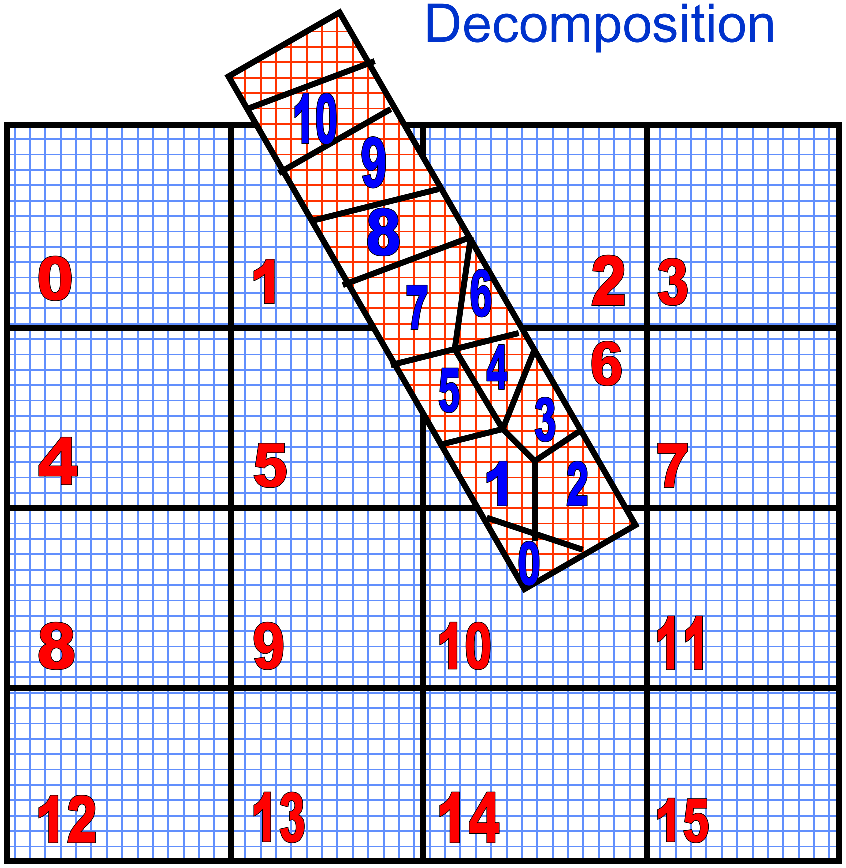
# Multiple Parallel Decompositions

**Pronto3D**
**- Mesh decomposition: graph based**
**- Contact decomposition: geometric**
**CTH**
**-Regular square decomposition**



# Processor Interactions Between CTH and Pronto3D

Pronto3D Mesh Decomposition




CTH Mesh Decomposition

## Processor Interactions

| CTH / PRONTO | Total |
|---|---|
| • 1 - 7, 8, 9, 10 | 4 |
| • 2 - 6, 7, 8, 9 | 4 |
| • 5 - 5, 7 | 2 |
| • 6 - 1, 2, 3, 4, 5, 6, 7 | 7 |
| • 10 - 0, 1, 2 | 3 |

- Overlapping data owned by different processors
- Pronto3D data and CTH mesh coordinates communicated to idle processors to load balance work

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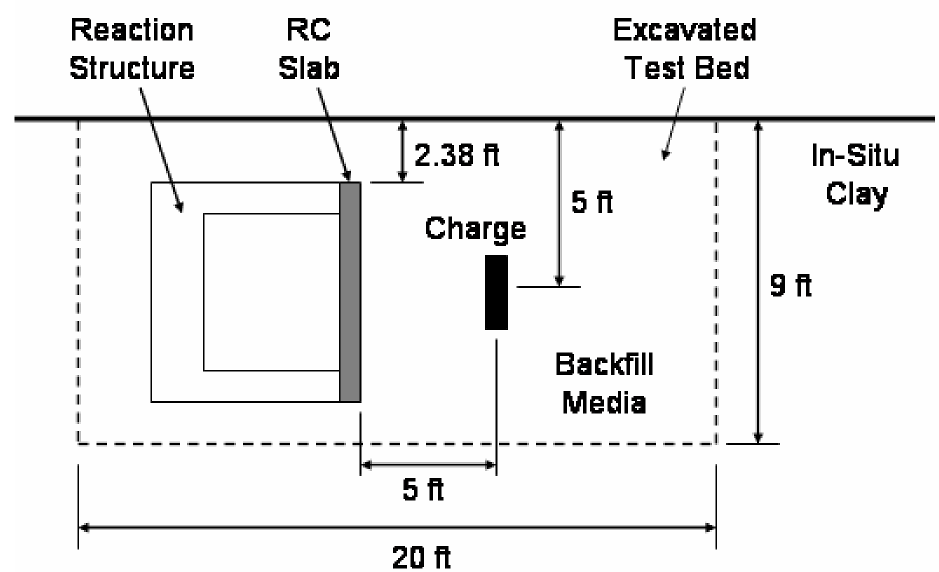
# Zapotec Application

- **Conventional Weapon Effects Backfill (CONWEB) Test Series**
  - **Conducted by Waterways Experiment Station in late 1980s**
  - **15.4-lb cased C-4 Charge at 5 ft standoff**
  - **Controlled backfill: sand and clay**
  - **Test Structure**
    - **Reinforced concrete (RC) slab bolted to reusable reaction structure**
    - **Slab thickness varied (4.3 and 8.6 inches)**
    - **Reaction Structure: 15 ft long, 65 inches high, 4 ft deep**
  - **Structure and soil instrumented**

- **Test 1**
  - **Clay Backfill**
  - **Slab thickness: 4.3 inches**

- **Test 2**
  - **Clay Backfill**
  - **Slab thickness: 8.6 inches**

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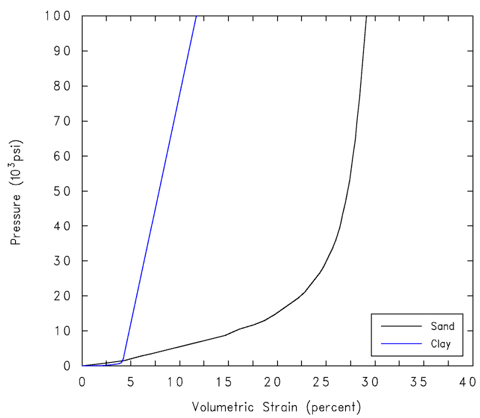
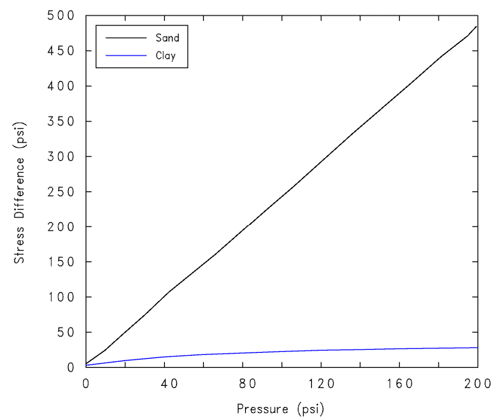
# Analysis Overview

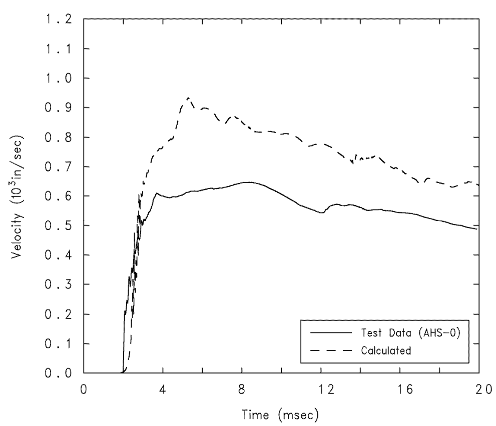
- Preliminary CTH analyses to develop material model for soil
  - Developed initial fit to hydrostatic and TXC data
  - Ran series of 2DC and 3D CTH standalone calculations to calibrate the model to better match measured free-field impulse and velocity data



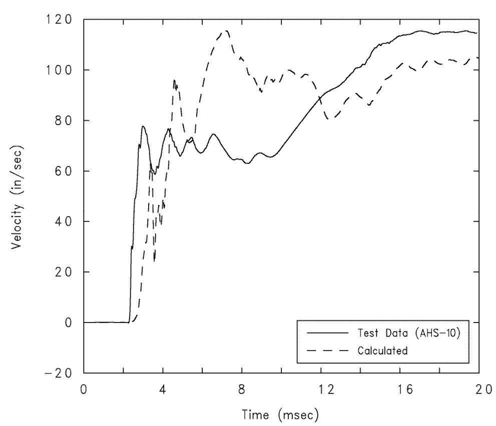




- Zapotec analysis
  - Soil and charge are Eulerian
  - Structure is Lagrangian
  - Comparisons
    - Interface impulse
    - Structure velocities
    - Slab permanent displacement
  - Many excursions calculations to assess modeling uncertainty

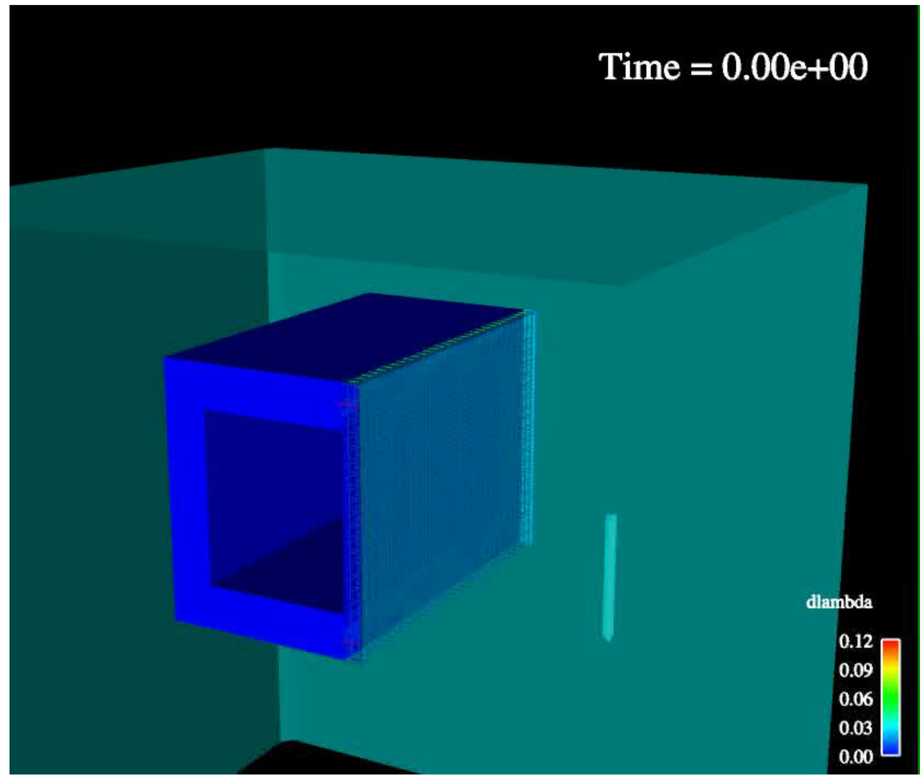
# Typical Results
# Test 1, Clay Backfill




AHS-0: Center of RC Slab




AHS-10: Base of Reaction Structure




RC Slab:
- Thickness: 4.3 inches
- Strength ($f_c'$): 6095 psi
- Reinforcement: 1.0 %

Backfill: Clay

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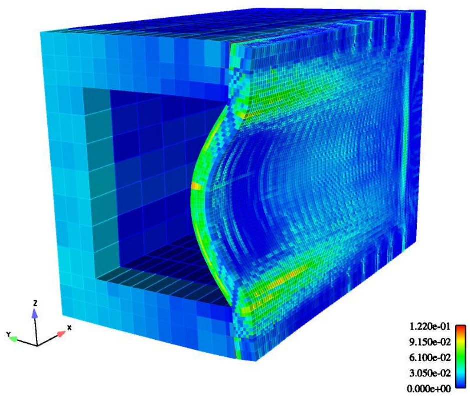
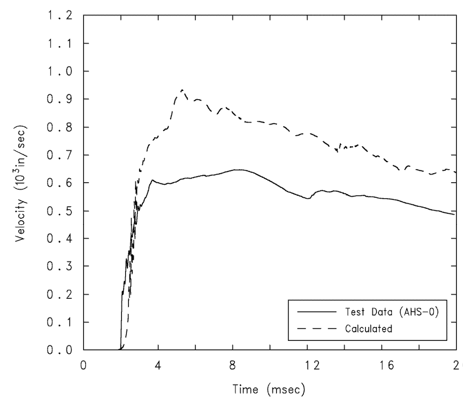
# Influence of Slab Thickness



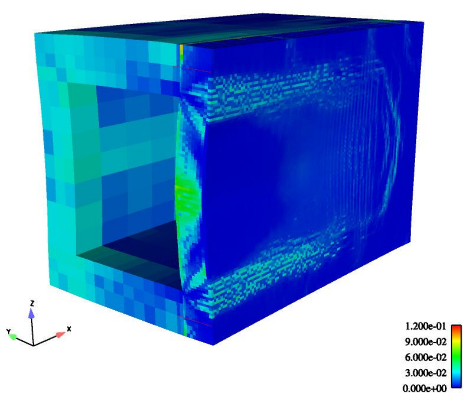



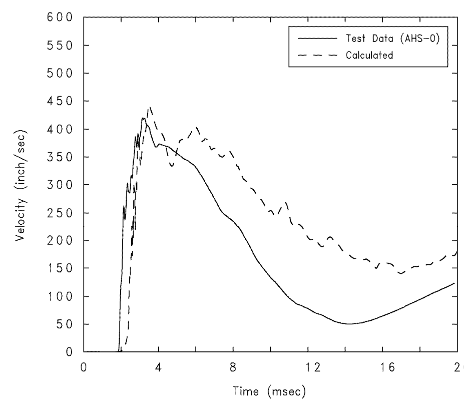

**Structure Response**

**Measured: Breach (18 x 51-inch)**

**Calculated: Failed concrete at slab center and along supports**

**Test 1, T = 4.3 inches (p = 1%)**




**RC slab is not breached in test or calculation**

**Light-to-moderate damage to RC slab**

**Permanent Displacement**

**Measured: 1.2 inches**

**Calculated: 1.4 inches**

**Test 2, T = 8.6 inches (p = 0.5%)**

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# Observations

- Coupled interaction arises from direct blast and rigid body motion of structure

- Fully coupled interaction over a long duration
  - Precludes use of one-way coupling
  - Most analyses run to 20 msec
  - Selected analyses run to 90 msec to recover permanent deflection

- Parameter study conducted to assess modeling uncertainties for Test 1
  - Assumed symmetry about charge
  - Treatment of bolted connections
  - Mesh resolution (CTH and Pronto3D)
  - Material modeling (rebar, concrete, and soil)
  - Variations in soil modeling had first-order effect on analysis

# Concluding Remarks

- CEL approach shows promise for modeling the blast/structure interaction problem
  - Automatically handles interaction from direct blast and structure rigid body motion
  - Avoids complicated data handling associated with one-way coupling
  - Handles coupling over extended times

- Modeling structural damage/breach is an open issue
  - Element death can be used to explicitly model breach
  - Investigation of appropriate failure/death criterion is underway

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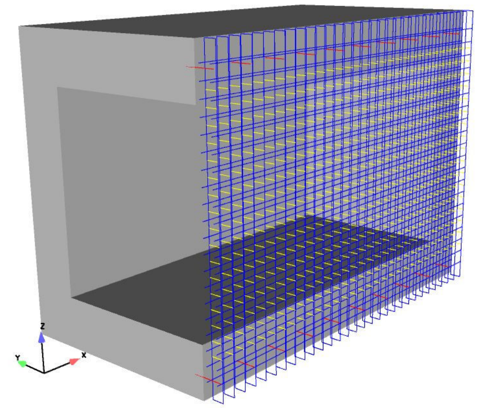
# Backup Slides

# Problem Development

- Pronto3D
  - Detailed FE mesh of structure
    - Reinforcement and bolted connections explicitly modeled
    - Approx. 80K elements
    - Resolution ~ 0.75 inch (1.9 cm)
  - Material Modeling
    - Concrete: K&C Concrete Model
    - Reinforcement: Rebar Model



- CTH
  - Meshing
    - Mesh extended well beyond the structure
    - Approx. 1.7 million cells
    - Resolution ~ 1.2 inch (3 cm)
  - Material Modeling
    - Charge: JWL Library EOS for C-4
    - Steel Case: Elastic-Plastic material
    - Soil: P-alpha EOS with Geologic (GEO) strength model